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Surface temperature inversion in the palsa and pounu fields of northern Finland

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Abstract

A very large surface inversion, which would not have been detected at the official recording height of 2 m above the mire surface, was recorded at the snow surface of an earth hummock in Lapland. The maximum inversion was 35 °C, and the monthly temperature departure was 7.8 °C in December 1992. The characteristics of the surface inversion are compared with conditions during another winter when no long inversion periods occurred. The presence of this surface inversion may explain the formation of new permafrost in pounus, even when official records showed no unusually low temperatures.

Keywords: Permafrost formation; Frost mound; Snow surface; Freezing index; Temperature gradient

1. Introduction

The nature of frost features that develop in subarctic conditions depends upon environmental characteristics such as the soil type, hydrology, snow cover, vegetation, and microclimatic at a particular location (e.g., Hjort, 2006). Attempts to explain such features using general climatological data can be very misleading (e.g., Seppälä and Hassinen, 1997). For example, the southern limit of the discontinuous permafrost zone crosses northern Fennoscandia and Finnish Lapland north of latitude 68°N (Brown et al., 1997). This essentially coincides with the −1 °C isotherm of mean annual air temperature (Heino and Hellsten, 1983; Atlas of Finland, 1987), and is equal to the southern limit of the permafrost zone (Rapp, 1982; Seppälä, 1988). The most typical visual features in this region are palsas, which are peat hummocks with a permafrost core (Seppälä, 1972), and in Finnish Lapland they can be up to 7 m high and 100 m in diameter (Seppälä, 1988).

Large areas of northern Lapland are also covered by small earth hummocks called *pounus* (in Finnish). Pounus are mainly formed of peat, and their cores usually contain only seasonal frost (Seppälä, 1998). They may be up to 1 m high and have a diameter of less than 2 m. The best-formed pounus develop on the edges of palsa mires (van Vliet-Lanoë and Seppälä, 2002).

The density of meteorological stations in northern Finland is low compared with the southern part of the country. Therefore, the local climate associated with mires containing palsas and pounus is poorly understood, and it is often difficult to explain their existence

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based on data from meteorological stations (Seppälä and Hassinen, 1997).

This study is part of a larger project that will consider the origin and development of pounus on Vaisjeäggi mire (69°49′N, 27°10′E), which contains palsa and pounu fields. The mire lies close to Skallovarri fell, and is about 10 km NE of the Kevo subarctic research station, which is also the location of one of the meteorological stations run by the Finnish Meteorological Institute (69°45′N, 27°01′E) (Fig. 1).

We monitored the winter temperatures of palsas and pounus and compared them with the official temperature recordings from Kevo station. For cloudiness, wind velocity, and snow depth measurements, we used data from Kevo, although our scattered recordings indicated that the wind and snow conditions differed significantly at the study site (Clark et al., 1985; Seppälä, 2002).

Our measurements at Vaisjeäggi proved extremely interesting, because new permafrost had formed in

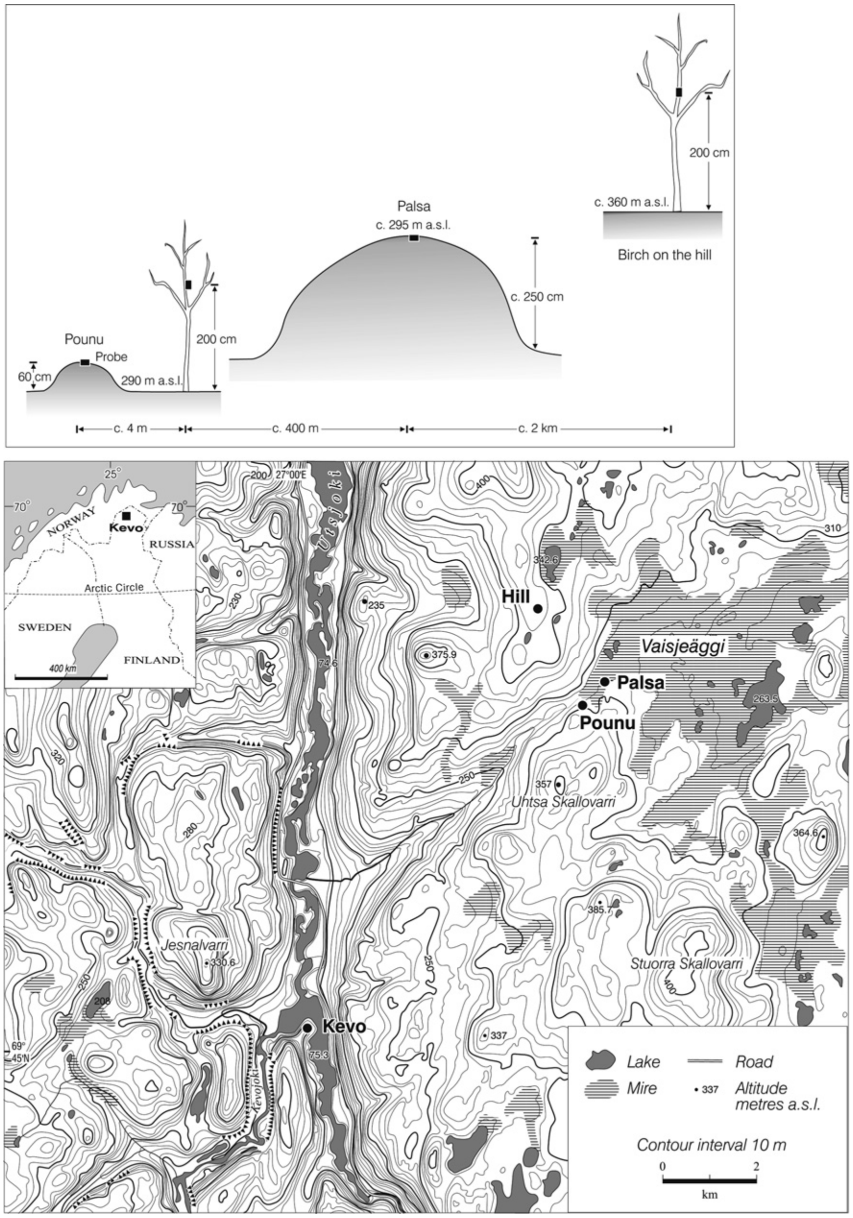

Fig. 1. Schematic representation showing the dimensions and locations of the palsa and pounu monitoring sites.

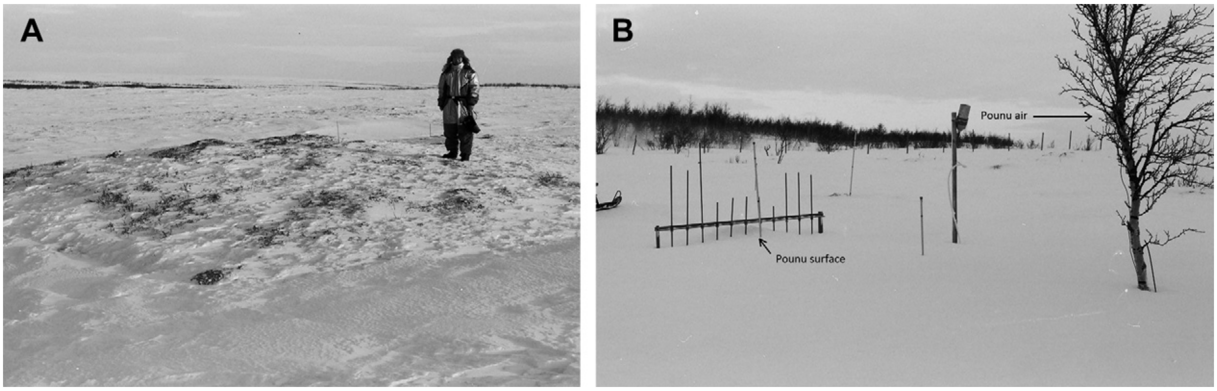

Fig. 2. Photographs showing the monitoring sites on (A) the palsa surface and (B) on the pounu surface and at the nearby air-sampling point (attached to a tree).

some of the pounus over the winter of 1993 (Seppälä, 1998). This raised the question of how to explain this deep frost penetration, as unusually cold winter was not recorded in the official meteorological data.

Our measurements revealed the existence of a thin layer of air that contained a temperature inversion, which Yoshino (1975) terms surface inversion. This phenomenon develops just at the snow surface, and has a significant impact on frost formation. Such surface inversion is not recorded by the standard meteorological measurements taken 2 m above the ground surface, but the critical height of frozen peat hummocks affected by this surface inversion is unknown. Consequently, we compared temperatures recorded on both palsas (2.5 m in height) and pounus (60 cm in height) (Fig. 2). The palsa had some 1.5 m of snow on its sides, while the surface of the pounu was just above the snow surface for most of the winter.

2. General conditions at the study site

In winter at Kevo, some 350 km north of the Arctic Circle, the sun remains below the horizon for around 50 days between the end of November and the middle of January. Winds during the polar night are weak, and during long periods of clear-weather emission, cooling is effective and a marked temperature inversion occurs in basins and at the bottom of valleys. Such temperature inversions can persist for more than a week.

This differs from the more common inversion, when, in winter and spring, strong diurnal and vertical temperature variations develop in the lower atmosphere. Savijärvi and Kauhanen (2001) reported strong nocturnal surface inversions during clear days in Sodankylä (67.3°N, 26.4°E). In that case, the 2 m temperature was −29 °C, and the snow surface temperature −36 °C (0600 UTC). During the following clear day (15 March 1997), there was active convection without inversion.

Kevo meteorological station is at an elevation of 100 m above sea level (a.s.l) and is located in a U-shaped valley formed by Pleistocene glacial erosion of a preexisting fault valley. An inversion has been directly or indirectly recorded during the winter in this valley by several investigators (Kallio and Lehtonen, 1973; Niemelä, 1979; Seppälä and Rastas, 1980; Tabuchi and Hara, 1992; Virtanen et al., 1998). This type of relief-controlled temperature inversion involving cold-air lakes is a common feature, not only in the valleys of northern Finland, but also in northern Sweden and Norway (e.g., Holmgren and Tenow, 1987; Huovila, 1987; Tenow and Holmgren, 1987; Tabuchi and Hara, 1992).

Details of the inversion in the Kevo Valley were reported by Tabuchi and Hara (1992, 1998), who established six temperature observation points from the lakeshore of Kevo Lake (70 m a.s.l.) to the summit area of Jesnalvarri fell (300 m a.s.l.) in the vicinity of Kevo station (Fig. 1). Their temperature recordings were conducted from 1989 to 1990. In December 1989,

Table 1
Mean midwinter (December–February) air temperatures at Kevo between 1992 and 1996, and their departure from the mean air temperature over the period 1962–1990.

Year	(D + J + F)/3	Departure
1992–1993	−8.5	+5.7
1993–1994	−14.3	−0.1
1994–1995	−9.1	+5.1
1995–1996	−12.7	+1.5

Table 2
Difference between the monthly mean air temperatures at Kevo over the period 1962–1990 and at the pounu site at Vaisjeäggi in the winters of 1992–1993 and 1995–1996.

Month	Kevo 1962–1990	Pounu 1992–1993	Difference	Pounu 1995–1996	Difference
November	−8.4	−9.4	−1.0	−9.7	−1.3
December	−13.4	−5.6	+7.8	−12.5	+0.9
January	−15.7	−8.1	+7.6	−7.0	+8.7
February	−14.1	−8.2	+5.9	−11.7	+2.4
March	−9.3	−8.0	+1.3	−6.5	+2.8
Mean	−12.2	−7.9	+4.3	−9.5	+2.7

a temperature inversion of 5 °C occurred in monthly mean air temperatures between the valley bottom and the summit 230 m above. At Kevo station, the temperatures in December 1989 were close to the long-term average temperatures. Consequently, we anticipated that on the Vaisjeäggi mire, which is located in a shallow basin at 300 m a.s.l. and surrounded by low fells up to 400 m a.s.l., inversion conditions would occur, although they would be much less pronounced on the summits compared with the

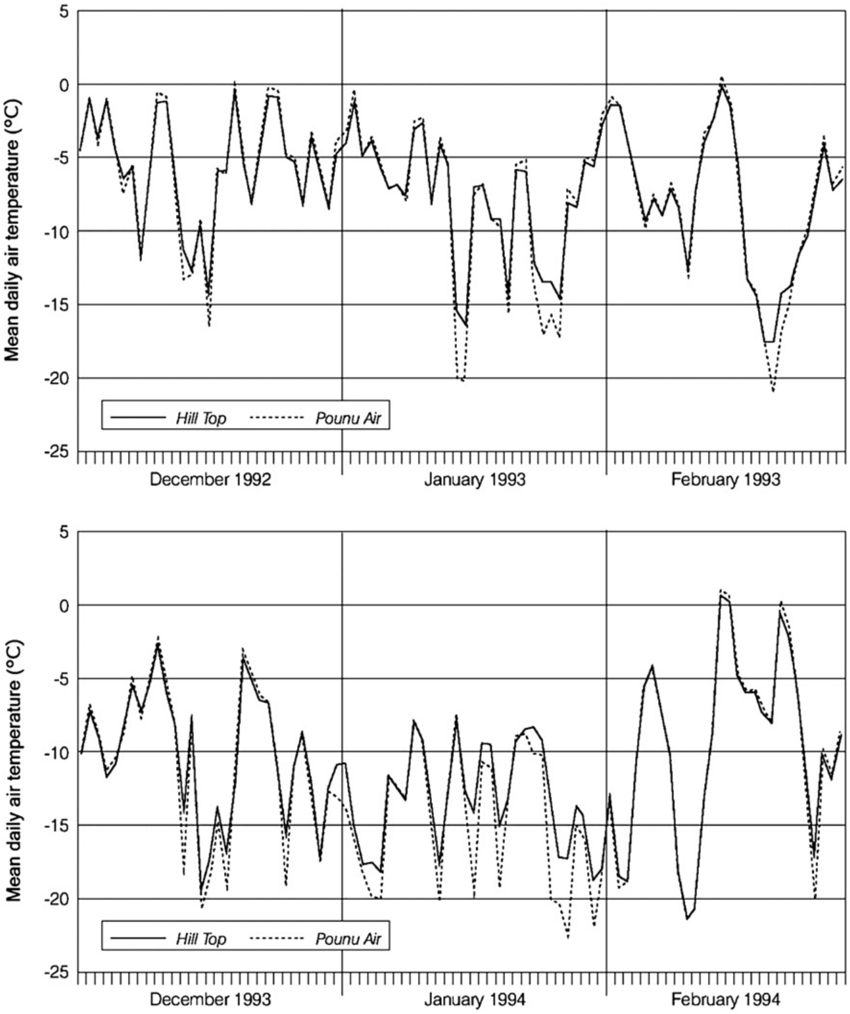

Fig. 3. Mean daily air temperatures at the monitoring sites on the hilltop, and 2 m above the ground surface at the pounu (see Fig. 2), over two winter periods.

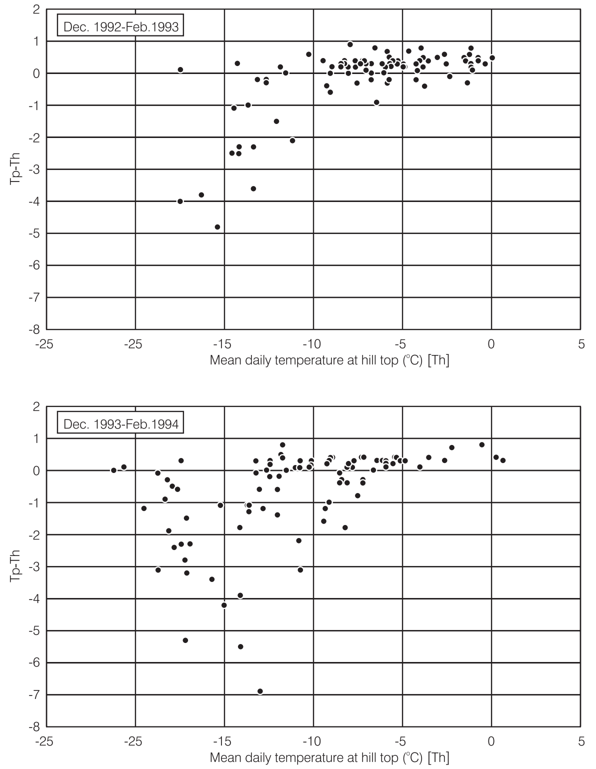

Fig. 4. Relationship between air temperature on the hilltop (Th), and the difference between air temperature at 2 m above the pounu (Tp) and on the hilltop (i.e., Tp−Th).

deep valley bottom at Kevo at 100 m a.sl., into which the Vaisjeäggi Valley also drains (Fig. 1). In this study, we shall compare the inversion at the higher elevation Vaisjeäggi mire with that at Kevo station.

3. Methods

Self-registering temperature loggers (DS-64K, Kona Sapporo Co.) with platinum resistance thermometer probes (resistance BDCB Jpt 100 (Ω) 5 mA class B CHINO) were placed:

(1) in a single birch (*Betula pubescens*) tree 2 m above the ground surface on a hilltop at 360 m a.s.l. to measure the air temperature;
(2) in a single birch tree on the pounu field in the valley bottom (290 m a.s.l.) to measure the air temperature 2 m above the mire surface;
(3) on the surface of a pounu 60 cm in height; and
(4) on a 2-m-high palsa located around 400 m up the Vaisjeäggi Valley (295 m a.s.l.) (Fig. 1).

To avoid direct solar radiation, the thermometer probes at the 2 m level were placed in small, well-ventilated, white wooden boxes. The probes on the ground surface were covered only by low natural shrubs a few centimeters in height.

Measurements on the hilltop were only made for 2 years because the cables were damaged by lemmings (*Lemmus lemmus*). Other measurements continued for the whole period; i.e., four years from September 1992 until August 1996. Temperatures were recorded at intervals of 1 h. In this study, we focus only on the winter (November–February) temperatures, when the inversions were observed.

4. Winter inversion at Vaisjeäggi

At Kevo, the mean air temperature over the three winter months (DJF) of 1992–1993 was rather high at −8.5 °C, but during the winter of 1993–1994 the DJF average of −14.3 °C was close to the long-term (1962–1990) average of −14.4 °C, according to the Finnish Meteorological Institute (Table 1). In the winter of 1994–1995, the DJF temperature was again considerably higher (difference +5.1 °C) than the long-term mean, while in 1995–1996, it was only a little higher (difference +1.5 °C). In November, the air temperatures at Vaisjeäggi were lower than at Kevo (Table 2), but from December to March the monthly means were often several degrees higher than at Kevo (Table 2), although Vaisjeäggi lies about 200 m higher than Kevo.

At Vaisjeäggi, the 2 m air temperatures on the hilltop and on the pounu field were similar, and during warmer periods, when the temperature approached 0 °C, the temperature in the Vaisjeäggi Valley was often somewhat higher than that on the hilltop (Fig. 3). The exception to this pattern occurred during colder periods, when the temperature in the valley was up to 7 °C lower, and a clear inversion situation could be identified. Such inversions were not so clearly developed during the rather warm winter of 1992–1993 as during the following year (Fig. 3). When the temperature on the hilltop dropped below −10 °C in the winter of 1992–1993, an inversion of up to −5 °C was always recorded. The lowest temperatures were not associated with the greatest inversions (Fig. 4). Daily mean temperatures below −20 °C were the same at both measurement sites (Fig. 3).

5. Surface inversion at Vaisjeäggi

The temperature differences at the pounu field and on the palsa were analyzed in detail over two winters (1992–1993 and 1993–1994) using data recorded

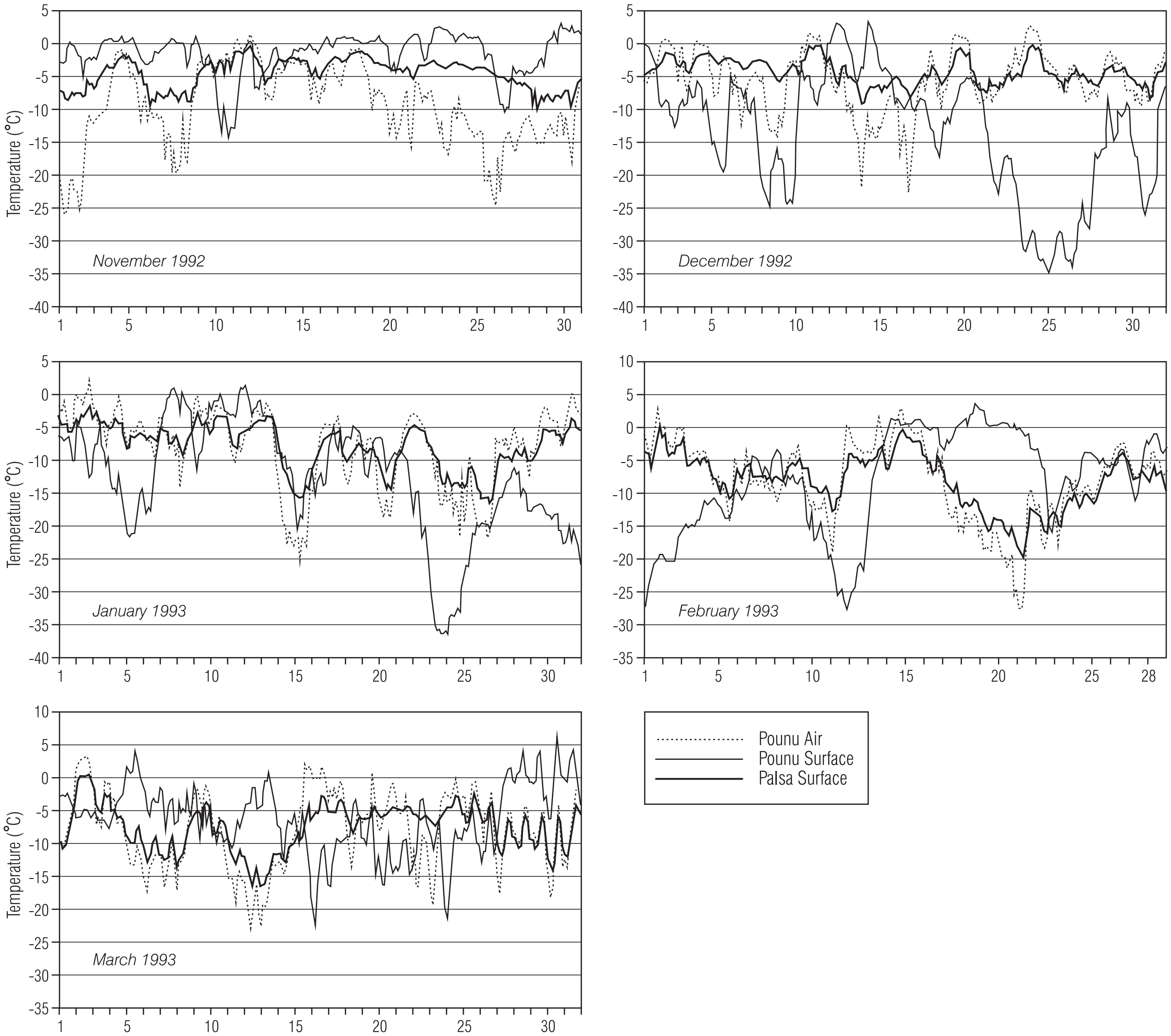

Fig. 5. Temperatures (averaged over 3-h intervals) of the Vaisjeäggi pounu and palsa surfaces, and of the air at 2 m above the surface of the pounu site, between November 1992 and March 1993.

every 3 h from the beginning of November to the end of March (Fig. 5).

In November 1992 (Fig. 5), the air temperature was generally much below the temperature recorded on the surface of pounu and palsa. The latent heat from the peat of the pounu kept the surface temperatures close to 0 °C. Normally, the surface temperature of the 2-m-high palsa was lower than that on the pounu surface, and they did not follow closely the changes in the air temperature. Occasionally (10–12 November 1992), the pounu surface was some 10 °C colder than the air temperature. Although the surface peat of the palsa froze, it still remained warmer than the air, and its temperature did not follow all of the daily variations of the air temperature. In early winter the subsurface part of active layer remained unfrozen, and so conducted heat to the surface.

December 1992 was relatively mild. The air temperature at the pounu site was only colder than −20 °C twice during the measurement period, but several very long-lasting (from 21 to 31 December) surface inversion periods developed, some of which were over 35 °C (Fig. 5). It must be remembered here that the height difference between the pounu surface and the probe in the tree measuring the air temperature was only 140 cm. On 24 December, the air temperature rose above freezing point, but the palsa surface temperature remained below zero and smoothly

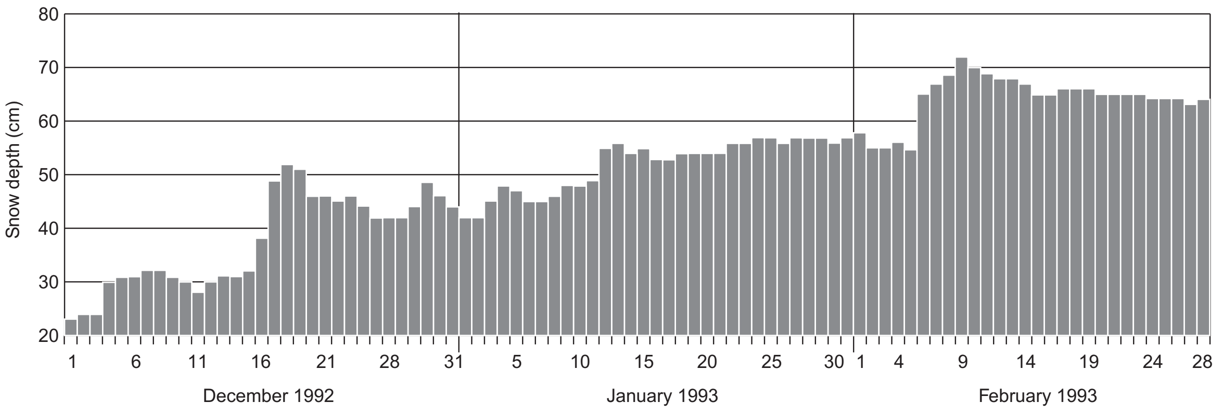

Fig. 6. Daily snow depths at Kevo station (December 1992 to February 1993).

followed the fluctuations in air temperature. Very small inversions were also noticed on the palsa surface (Fig. 5).

Surface inversion periods occurred in both January and February 1993 (Fig. 5). Surface temperatures on the palsa surface followed the air temperatures very closely. From 16 to 22 February, a warm period was recorded on the pounu, although air temperatures were much lower (Fig. 5), possibly because new drifting snow covered the pounu. An increase in snow cover had taken place already at Kevo at the beginning of February (Fig. 6). When considering the microrelief in winter, it must be remembered that the steep slopes of pounus and palsas collect snow and become buried beneath a smoothly undulating snow surface. If the summit of a palsa is 2 m high, then it only rises 30–50 cm above the surrounding snow surface and only the summit is snow-free. In midwinter, the surface of the pounus, at 60 cm in height, is often just at the snow surface, and may be covered by snow during periods of calm weather, although it is readily uncovered by the wind (Fig. 2).

The next longest surface inversion period took place in the second half of March (Fig. 5). In this month, the diurnal rhythm of the temperature fluctuations can be clearly observed (Fig. 5), with daytime temperatures high because of solar radiation, and outgoing radiation causing especially low nighttime temperatures on the surface of the pounus. This is a quite normal diurnal inversion.

The winter of 1993–1994 was much colder according to the meteorological observations at Kevo (Tables 1 and 2); consequently, temperature fluctuations at the palsa and pounu sites are provided for comparison (Fig. 7). The inversions were very limited, and occurred on only a few days, and temperature fluctuations on the surface of the pounu and palsa closely followed the air temperature.

6. Monthly winter temperatures during 1992–1993 and 1995–1996 at the palsa and pounu sites

A comparison of monthly mean surface temperatures on the palsa and pounu in 1992–1993 clearly demonstrates that December (by c. 9 °C) and January (by c. 5 °C) were much colder on the pounu than on the palsa (Fig. 8) during that rather mild winter (Table 1) in which December was especially mild (Table 2). From February 1993 onwards, the mean surface temperatures did not differ significantly (Fig. 8).

The maximum temperatures on the pounu were recorded in the winter of 1992–1993 and were 2–4 °C higher than on the palsa surface, but were much lower (4–10 °C) in April and May 1993. The minimum temperatures follow the same pattern as the monthly means: the surface of the pounu was much colder than the palsa surface until March 1993.

The winter of 1995–1996 was relatively normal regarding its air temperature regime (Table 1), and the monthly means, and the maximum and minimum surface temperatures on the palsa and pounu, all closely followed each other (Fig. 8) with no signs of inversion. The pounu surface was somewhat warmer than the palsa surface.

7. Freezing indices in the winters of 1992–1993 and 1993–1994

Monthly freezing indices were derived from the daily mean temperatures at all four measurement sites. Table 3 lists the temperature differences and fluctuations

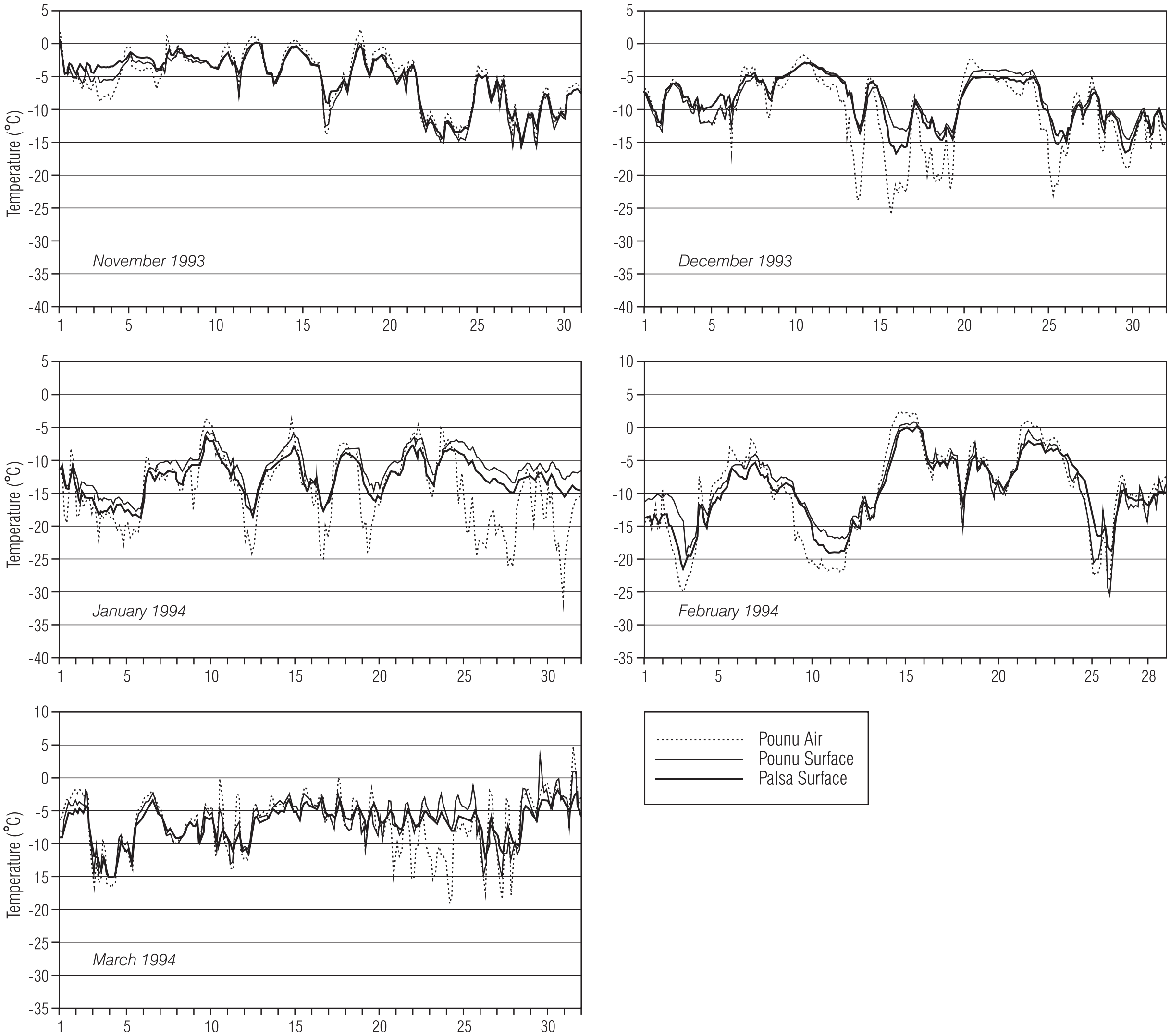

Fig. 7. Temperatures (averaged over 3-h intervals) of the Vaisjeäggi pounu and palsa surfaces, and of the air at 2 m above the surface of the pounu site, between November 1993 and March 1994.

between the Vaisjeäggi pounu site and Kevo Meteorological Station. Air temperatures in 1992–1993 were only a little higher than in 1993–1994, and in both years the winter was only a little colder in Vaisjeäggi Valley than on the hilltop (Fig. 3).

In early winter (October and November) of 1992, air temperatures were much lower than on the surface of the pounu and palsa, but in December and January, the inversion had a dramatic effect on the pounu surface (Tables 4 and 5). The temperatures on the palsa surface in December 1992 were surprisingly high, and later in the winter (January–April 1993) were very similar to the air temperatures (Table 5; Figs. 5 and 7). On the palsa, the surface temperature during these eight months was about 1.5 °C higher than the air temperature at the pounu site. This indicates that the 2.5-m-high palsa was above the strongest surface-inversion layer for most of this period.

In May, the mean monthly air temperatures in northern Lapland are typically close to 0 °C, but in 1993 the surface of the pounu was unusually cold (average −5.3 °C). This caused strong freezing, and frost formation. The frozen peat in the pounus has a high thermoconductivity (Kujala et al., 2008).

The total freezing index on the palsa surface in 1992–1993 was unusually low (1199.1) compared with a mean freezing index at Kevo of 2052.7 (see Seppälä and Hassinen, 1997). Of note, the pounu

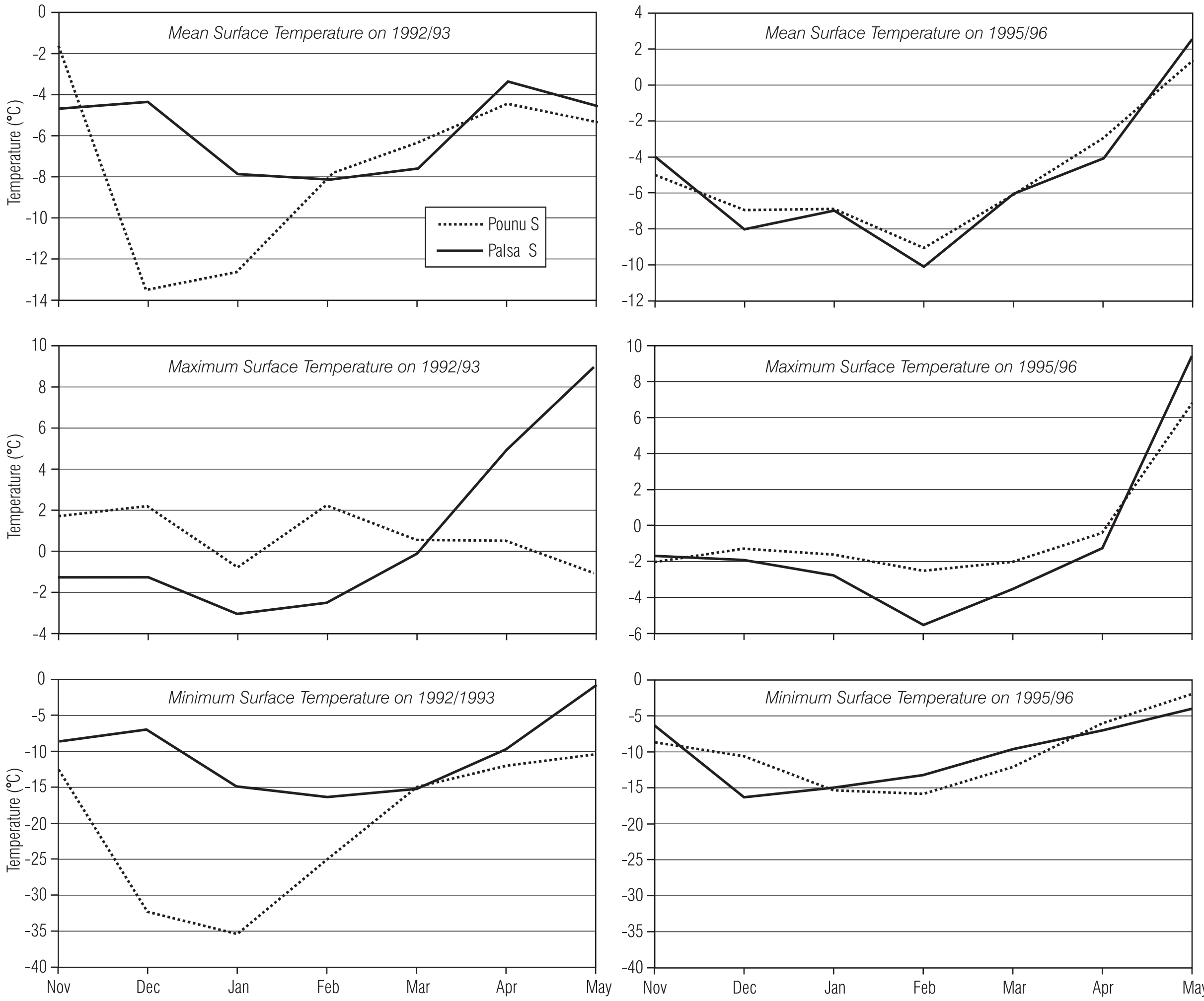

Fig. 8. Monthly mean surface temperatures, and absolute maximum and minimum temperatures in the month, on the pounu and palsa surfaces at Vaisjeäggi from November to May in 1992−1993 and 1995−1996.

surface had the highest freezing index (Table 6) during this rather mild year (Table 3).

Comparing the pounu and palsa surface-freezing indices (Table 6), it is evident that the inversion actually affected just the snow surface, and did not affect the 2-m-high palsa, which suggests that the inversion layer was about 1 m thick. In November and December 1992, the latent heat of the active peat layer (c. 60 cm thick) presumably kept the pounu surface temperature above the air temperature.

Conditions during the winter of 1993−1994 were closer to the normal freezing index distribution. January was the coldest month and inversions did not cause great irregularities in temperatures. The pounu

Table 3
Differences of mean monthly air temperatures at Vaisjeäggi the pounu site compared with the mean values observed at Kevo meteorological station (1962−1990).

Year	Nov	Dec	Jan	Feb	Mar	Mean
1992−1993	−2.4	+6.2	+4.5	+6.3	+0.8	+3.1
1993−1994	+2.9	−0.4	−4.3	+4.5	+2.3	+1
1994−1995	−0.7	+5.4	+3.8	+6.1	+5	+3.9
1995−1996	−4.3	−3.1	+6.4	+1.3	+2.2	+0.5

Table 4
Midwinter mean air temperatures at pounu site on Vaisjeäggi mire in winters 1992–1996.

Year	December	January	February	(D + J + F)/3
1992–1993	−5.6	−8.1	−8.2	−7.3
1993–1994	−10.5	−14.6	−9.6	−11.6
1994–1995	−6.2	−8.5	−8.3	−10.4
1995–1996	−12.5	−7.0	−11.7	−10.4

surface was somewhat colder than the corresponding air temperature only in November and May. In January 1994, only the hilltop was clearly milder than the air in the valley. Through the whole winter, the temperatures on the pounu and the palsa did not differ significantly, and the total freezing indices at both sites were similar, and lower than at the air-temperature monitoring sites.

8. Surface inversion and general weather conditions in December 1992 and February 1993

We do not have daily meteorological observations from the study site itself, and we know that the conditions at Kevo, in the deep valley, often differ from the conditions at our study site. However, Figs. 9 and 10 show cloudiness and wind speed observed at Kevo station, together with the surface temperatures on the pounu and palsa, and the air temperature at the pounu site, over two months (December 1992 and February 1993) that experienced surface inversion periods. With some exceptions, we can conclude that clear weather and low wind speeds support the development of the surface inversion. Increasing cloudiness results in a rising surface temperature. However, the weather conditions during the inversions almost certainly differed from the conditions at Kevo, 10 km away in a deep valley.

From 15 to 23 February 1993, there was a long period of exceptionally high surface temperatures on the pounu (Figs. 5 and 10). The weather at Kevo was relatively clear, wind speed was low, and the air temperatures at the pounu site were the lowest of the winter. These should be the ideal conditions for the development of a surface inversion. We measured the snow depth on the pounu on 1 March, and at that time there was 10 cm of snow on the pounu (at Kevo, 58 cm). The pounu was 60 cm high above the flat surface of the mire, which then had a 49 cm snow cover. Thick snow on the pounu might have been expected earlier in February 1993 because at Kevo the snow thickness increased between 5 and 9 February from 55 to 72 cm (Fig. 6). However, there was still a clear inversion on the pounu between 9 and 14 February. It seems that drifting snow had covered the pounu. An alternative explanation for the high surface temperature on the pounu could be solar radiation, but this is considered unlikely because of the diurnal temperature variation (see Figs. 5 and 10). Evidence that the palsa surface was not covered by thick snow in the second half of February comes from the low temperatures and associated diurnal fluctuations (Fig. 5). As the palsas are higher than the pounus, drifting snow accumulates on their flanks, but the summits remain clear (Seppälä, 1990, 1994).

9. Discussion

Yoshino (1975) explained temperature differences over small areas based on differences in the surface characteristics. The nature of the surface cover (e.g., sandy soil, grassland) has a great impact on microclimatic conditions. A temperature inversion close to the surface that develops in association with sunset and outgoing radiation during calm and clear weather is a common feature in all types of climates (Geiger, 1966; Berényi, 1967), but this is not the case in Lapland in winter, when the sun is below the horizon for a period of almost two months. In this study, the surface was essentially the same mire surface, with wet peat basins and drier mounds, which were then covered by (and later emerged from under) snow that smoothed out the microrelief as the amount of snow increased.

Table 5
Monthly mean surface temperatures at pounu site and on palsa at Vaisjeäggi in winters of 1992–1996. See examples of minimum and maximum temperatures in Fig. 8.

Month	1992–1993			1995–1996		
	Pounu air	Pounu surface	Palsa surface	Pounu air	Pounu surface	Palsa surface
November	−9.4	−1.6	−4.6	−9.7	−4.8	−3.7
December	−5.6	−13.4	−4.3	−12.5	−6.9	−7.9
January	−8.1	−12.6	−7.8	−7.0	−6.7	−6.9
February	−8.2	−7.9	−8.1	−11.7	−8.9	−10.2
March	−8.0	−6.3	−7.6	−6.5	−6.1	−6.0

Table 6
Monthly freezing indices derived from daily means at the four monitoring sites (Fig. 1) in 1992–1993 and 1993–1994.

Month	1992–1993				1993–1994			
	Hill air	Pounu air	Pounu surface	Palsa surface	Hill air	Pounu air	Pounu surface	Palsa surface
October	220.6	243.2	33.9	108.6	132.6	136.8	118.7	90.1
November	268.3	282.7	56.4	139.3	169.1	163.4	180.1	159.0
December	174.5	173.6	418.3	134.6	312.9	326.9	264.7	270.9
January	238.4	251.3	390.4	241.5	404.7	453.2	348.8	390.3
February	227.4	230.0	225.2	228.0	269.6	272.0	255.2	270.7
March	244.0	248.5	197.0	235.5	227.1	221.9	197.6	211.4
April	137.5	131.1	133.1	110.2	40.6	39.0	16.0	30.0
May	7.1	3.3	163.5	1.4	10.0	6.8	0.2	1.9
Total	1517.8	1563.7	1617.8	1199.1	1566.6	1619.0	1381.3	1424.3

The steep gradient in air and surface temperatures was surprising. The 30 °C temperature difference over the 140 cm height difference was considerably greater than was expected. Another unexpected aspect was that the inversion stratum during a warm winter was thin but very intense. This indicates that the thickness of the inversion layer does not depend on the air temperature alone. The deepest frost penetration took place in a winter (1992–1993) that, according to the official meteorological recordings at Kevo, was mild, at 5.7 °C warmer than the mean 1962–1990 temperature (Table 1).

Because the aim of this research was to investigate the local conditions on pounus and palsas, temperature probes were not placed at numerous different heights above the ground surface. To study the surface inversion on the snow surface, a probe that remains above the snow surface, or a series of probes, would have been needed. This became clear during the measurement period of February 1993, when the pounu surface was covered by drifting snow and the temperature rose above 0 °C, while the air temperature dropped below −27 °C.

This surface temperature inversion is a rare phenomenon that does not occur every winter. It appears that when three factors (i.e., calm weather, clear skies, and outgoing radiation) act together, it is possible for a very large temperature inversion to develop on the snow surface. This was clearly observed in our field measurements. By using the Stefan–Boltzmann radiation law (i.e., that the total energy emitted by a blackbody surface is proportional to the fourth power of the absolute temperature), we concluded that during the polar night, when the sun stays below the horizon, snow behaves as a blackbody surface with an emissivity of $\varepsilon = 1.0$, so that when the temperature is around −15 °C (c. 260 K), its irradiance is approximately 260 Wm^{-2}. This high irradiance causes the large temperature inversion. In the middle of winter in Lapland, on pounu and palsa surfaces that are free of snow, there is only outgoing radiation and a negative energy balance, and this causes the deep frost formation in the peat layers.

A close examination of air and pounu surface temperatures for the winter of 1992–1993 (Fig. 5) shows some remarkable patterns. Between November and February, there are several cases when the pounu surface temperature rose above 0 °C (23 and 30 November, 13 and 15 December, 8 and 12 January, 15 and 19 February, and 6 and 13 March). During these events, the pounu was probably covered with snow and, simultaneously, the air temperature was negative and decreasing. Latent heat from water in the mire can probably explain the early winter cases, the covering snow on the pounu explains the midwinter cases, and in February and March, solar radiation would be able to heat the surface of the snow-covered pounu. On a sunny day, solar radiation also causes temperatures under the snow to rise above freezing, as shown in Antarctica (Seppälä, 1992). Furthermore, our instrumentation worked perfectly well, and the probes where checked after the measurements.

Surface inversions that lasted several days had a great impact on frost formation in the pounus. We recorded frost depths in a pounus, and in the surrounding peat layers, and confirmed that new permafrost formed in the pounus during the winter of 1992–1993 (Seppälä, 1998), and persisted until at least September 2005. The official meteorological measurements at Kevo do not give any signal of great changes in air temperatures during the past 10 years, but the surface inversion can explain the very intense, spot-like, frost formation that has been observed in several pounus in northern Lapland (Luoto and Seppälä, 2002). Similar inversions surely occur everywhere on the snow surface, but thick snow is a good insulator, and therefore a thick frost layer only forms where the snow cover is thin (Seppälä, 1990, 1994), or in palsas and pounus that rise above the snow surface.

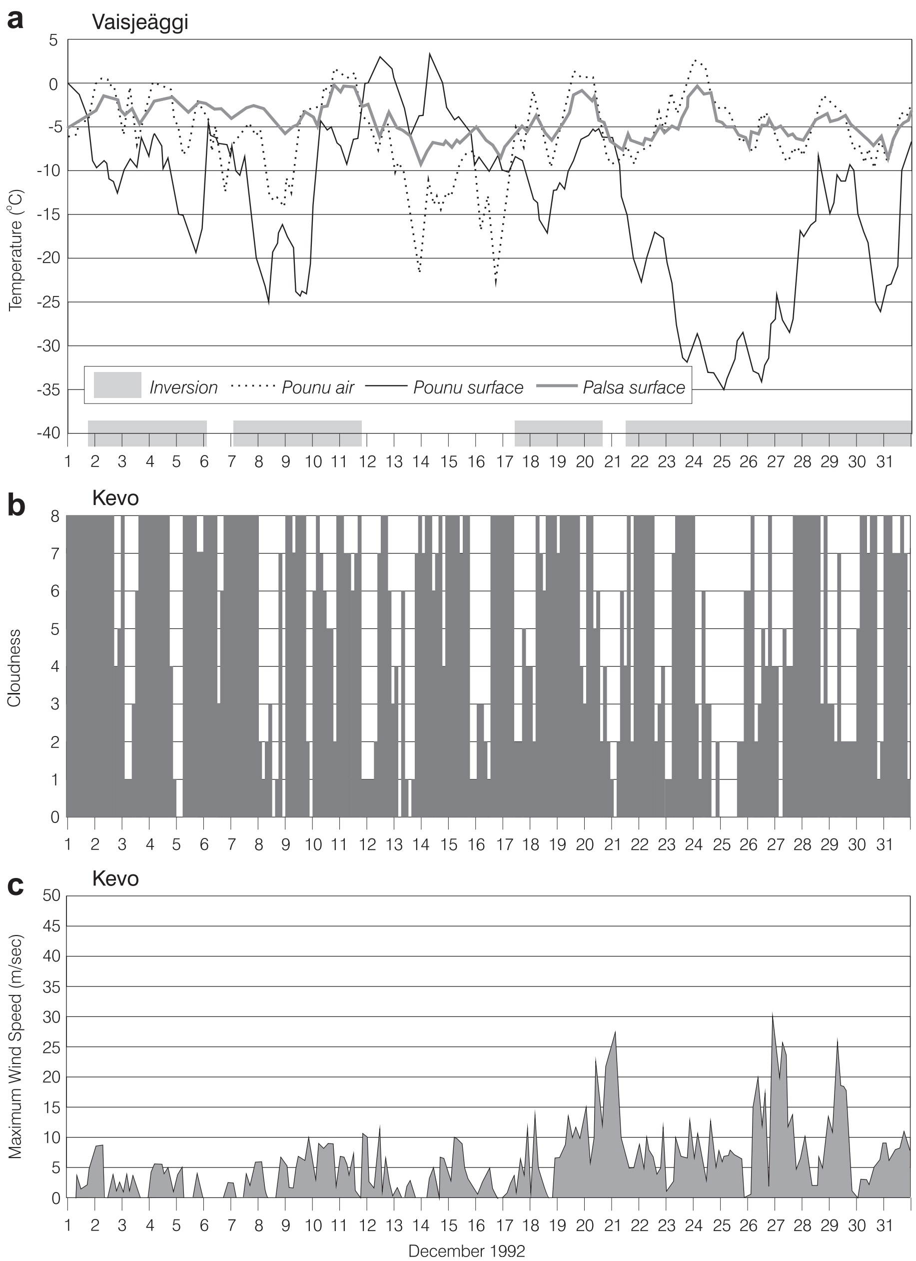

Fig. 9. Meteorological observations from December 1992. (a) Temperatures at Vaisjeäggi on the pounu and palsa surfaces, and the air temperature at 2 m above the pounu surface, recorded every 3 h. (b) Cloud cover (octas) and (c) maximum wind speed (m/sec) recorded every 10 min in each 3-h period at Kevo.

In 2001, observations of several pounus in a larger area of Finnish Lapland were made, and it was noted that many pounus had a permanently frozen core (Luoto and Seppälä, 2002). There were clear vegetation differences between pounus with and without permafrost. On the permanently frozen pounus, the vegetation was patchier, with low-growing species indicating drier conditions and thin snow cover.

Topography is the main factor controlling the observed temperature inversion. The monthly mean temperature difference between the Kevo Valley and the Jesnalvarri hilltop, at 230 m above the lake level, was 5 °C in winter (Tabuchi and Hara, 1998). The height difference between our hilltop site (360 m) and the pounu field (290 m) at Vaisjeäggi is only 70 m, and the valley is shallow with few undulations; consequently,

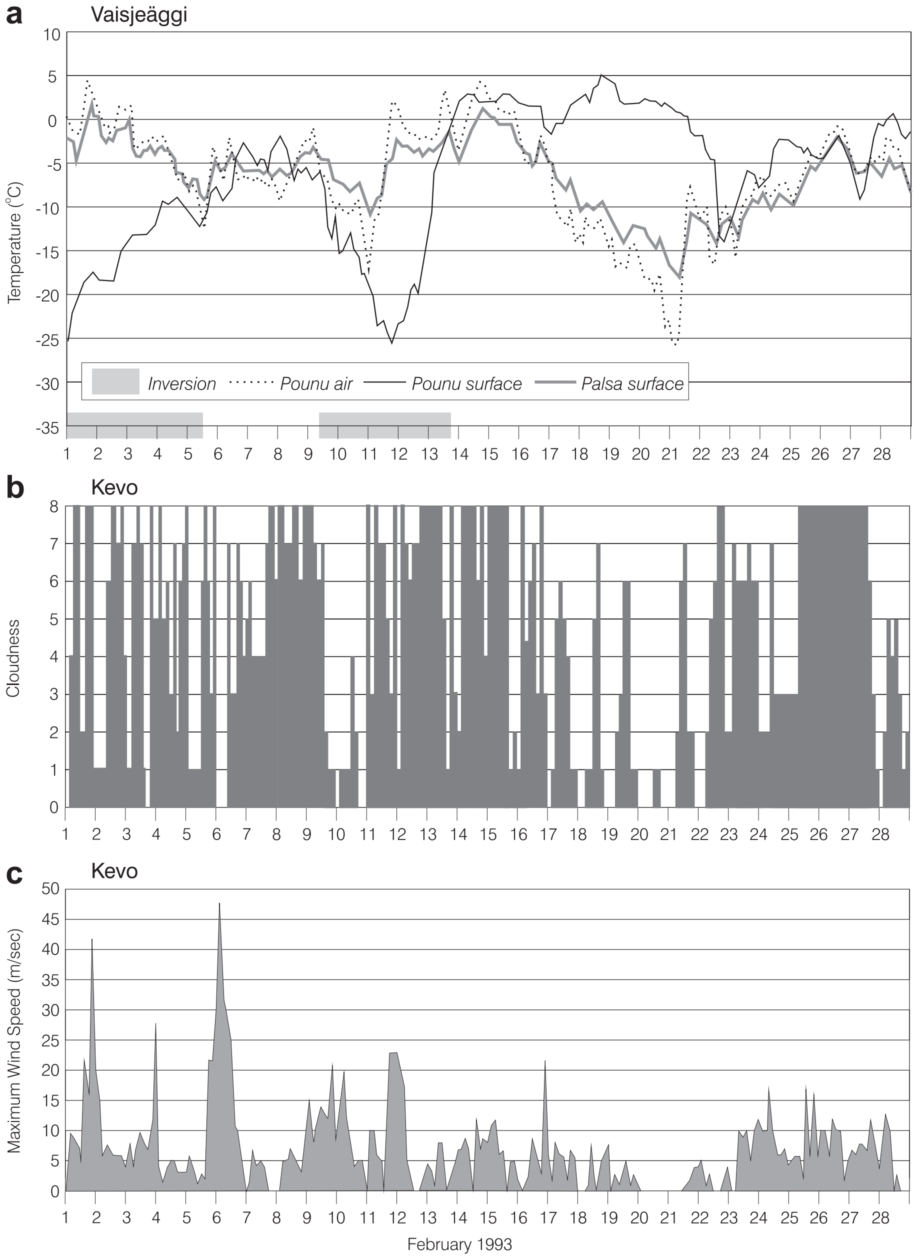

Fig. 10. Meteorological observations from February 1993. (a) Temperatures at Vaisjeäggi on the pounu and palsa surfaces, and the air temperature at 2 m above the pounu surface, recorded every 3 h. (b) Cloud cover (octas) and (c) maximum wind speed (m/sec) recorded every 10 min in each 3-h period at Kevo.

the temperature inversion is only about 1 °C, based on the monthly mean air temperatures. The greater height above sea level probably leads to a reduction in the intensity of the inversion.

It has become clear from these observations that the mean annual air temperatures on the fell summits are often higher than those in the valleys, and that the local altitude combined with a temperature gradient of 0.6 °C/100 m cannot be used to calculate summit temperatures. The gradient is valid only for the free atmosphere, not for varying relief surfaces on which the temperature and density of the air differs and causes surface drainage.

The most intensive surface inversion occurs when there is clear weather that allows emission cooling to take place. In late December 1992, a surface inversion of 35 °C persisted for about 10 days. During this period at Kevo station, 10 km away, there were extended periods of completely overcast skies and maximum wind velocities exceeding 30 m/s (Figs. 9 and 10). These winds, however, did not destroy the existing inversion at the study site.

Our observations lead to the question of why strong surface inversions only developed during mild winters. The probable reason is that when the air temperature is, for example, below −40 °C, the cold air layer is so thick that the surface inversion does not occur because the normal inversion layer is hundreds of meters thick in the valleys and acts as a cold-air drainage lake.

10. Conclusions

The winter of 1992–1993, which was classified meteorologically as a mild winter, was the only one of the five studied here during which a strong surface inversion developed; therefore, it can be considered an unusual year because new permafrost also formed under these particular conditions. During some winters, such as in 1984–1985, new small palsa embryos formed (Seppälä, 1986), but they have not grown any bigger. Snow depth has been identified as the main controlling factor for palsa formation in this environment (Seppälä, 1982, 1986, 1988, 1990, 1994), but the combination of the surface inversion together with thin snow cover can probably explain the penetration of frost to unusually great depths in the mires at the initial stage of palsa formation. Once the permanently frozen core of the palsa has been formed and has risen well above the mire surface, then unusual coldness is no longer required to keep its core frozen. Low mounds are affected by the surface inversion, but not higher ones.

The results of this study strongly suggest that it may be unwise to use meteorological data recorded some distance from a study site to correlate and interpret geomorphological phenomena. Often, standard meteorological readings are unable to provide the necessary information concerning important phenomena, such as surface inversions, or other situations likely to promote greater frost penetration.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.polar.2012.10.001.

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